SRF and warm RF components for CeC PoP Experiment in RHIC

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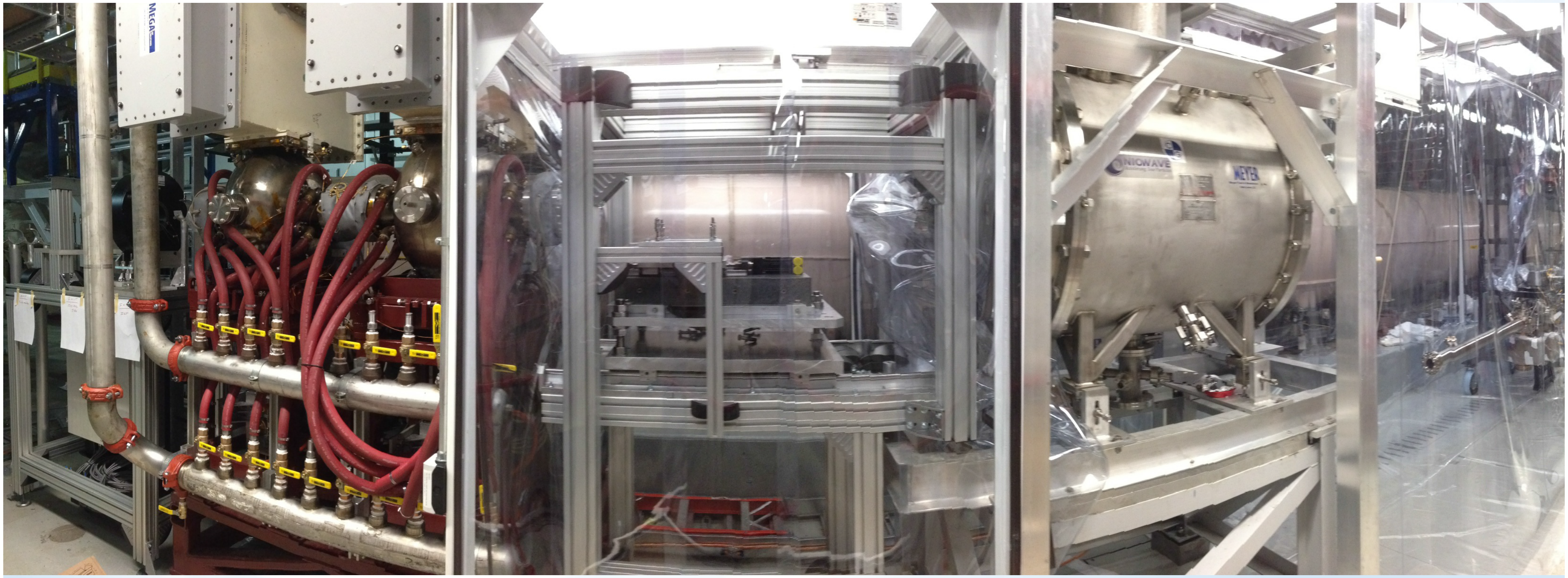
Outline

- Overview: layout and general description of the CeC PoP linac
- Design, parameters, status, test plans, and milestones for:
  - 112 MHz SRF gun
  - 500 MHz bunching cavities
  - 704 MHz 5-cell SRF accelerating cryomodule
- Summary

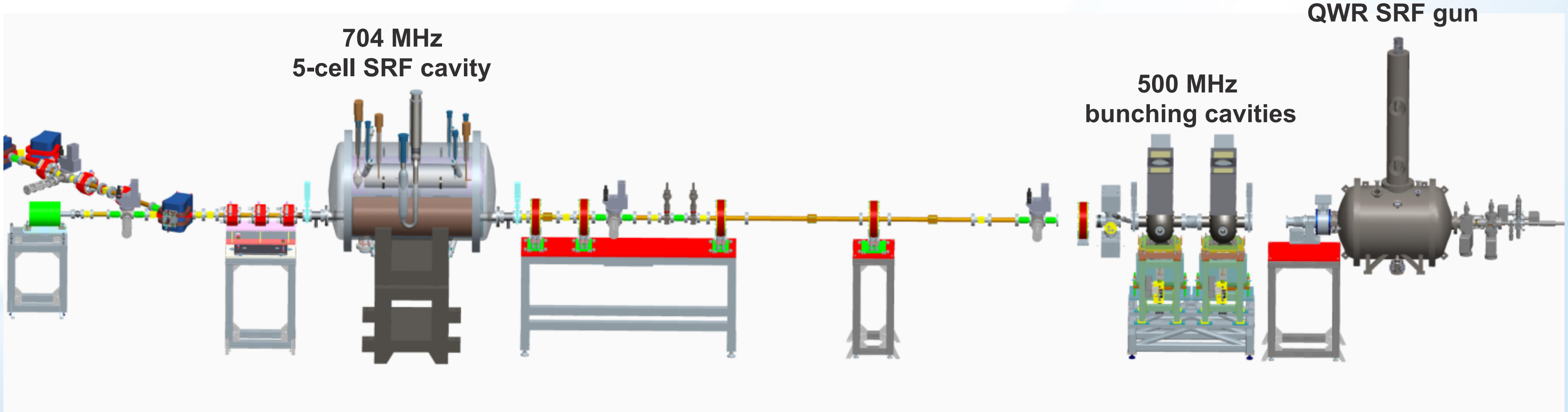


Bunching cavities

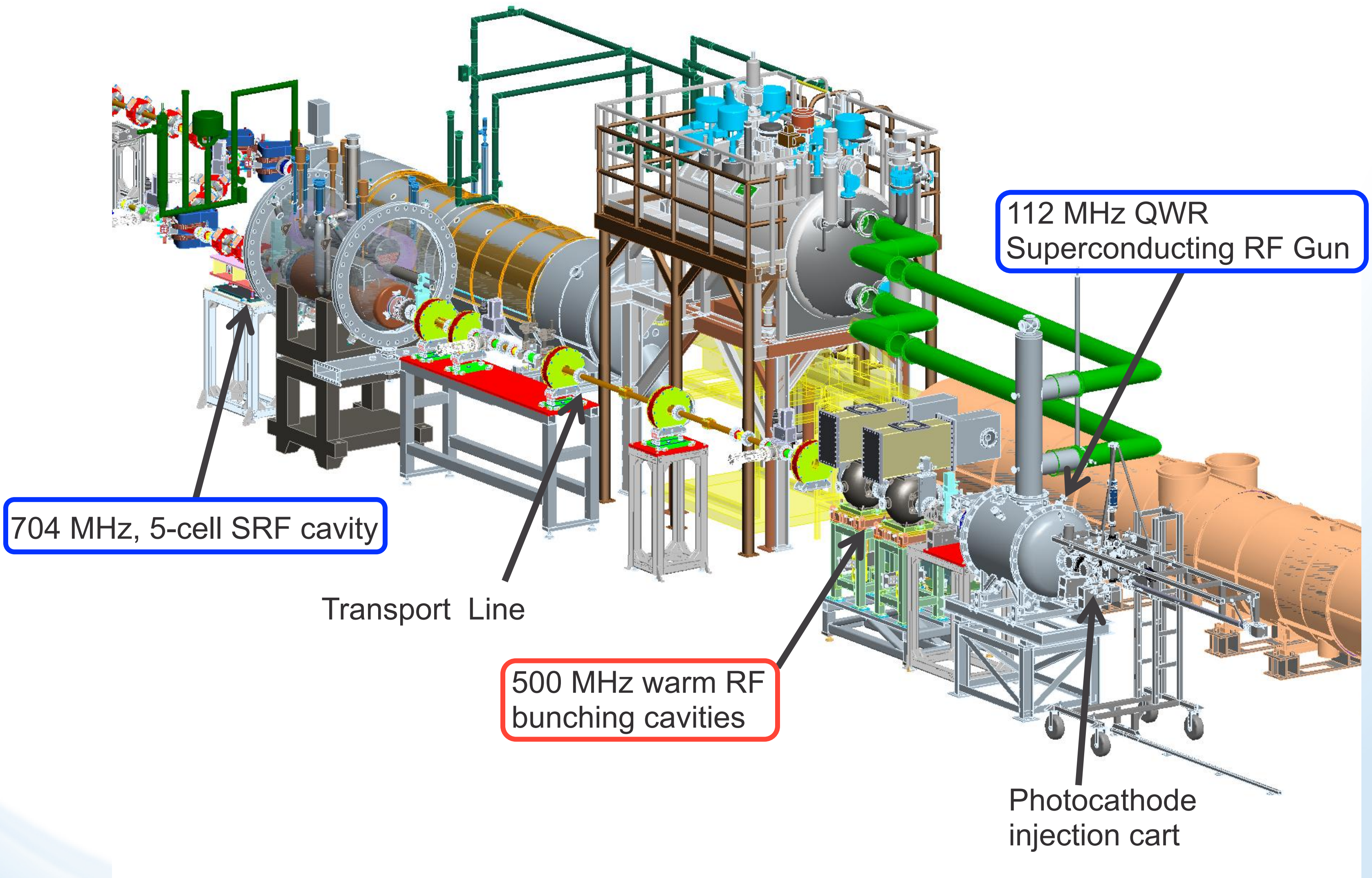
112 MHz SRF gun

Overview

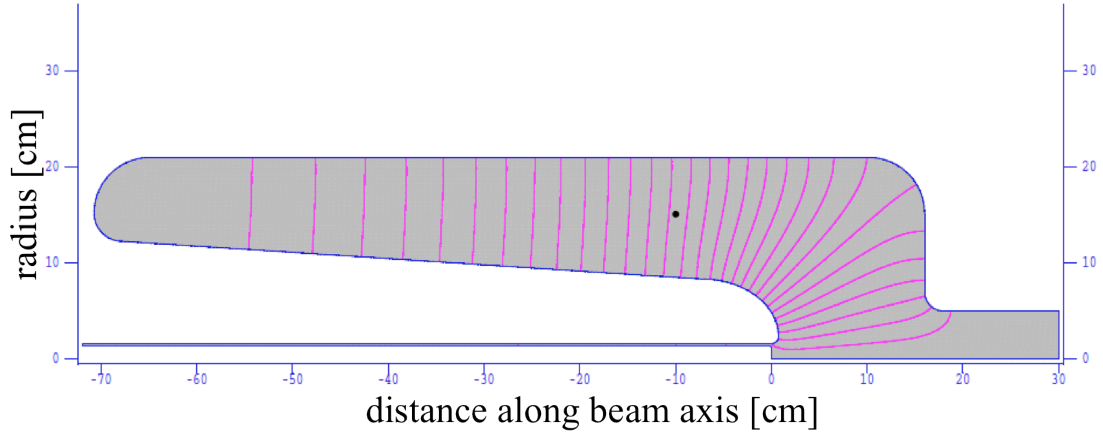
- There are three SRF/RF systems in CeC PoP linac set up:
  - A Quarter-Wave Resonator (QWR) type SRF gun, operating at 112 MHz. This gun will generate 2-MeV, high charge (several nC), low repetition rate (78 kHz) electron beam.
  - Two normal conducting 500 MHz single-cell bunching cavities, on loan from Daresbury Lab. The cavities were formerly used in SRS.
  - A 704 MHz 5-cell SRF cavity (BNL3) to boost the energy of electrons to 22 MeV.
- RF power amplifiers and LLRF electronics are located in building 1002B.
- 4 K and 2 K cryogenic systems are located in the tunnel and nearby buildings.



CeC PoP linac layout



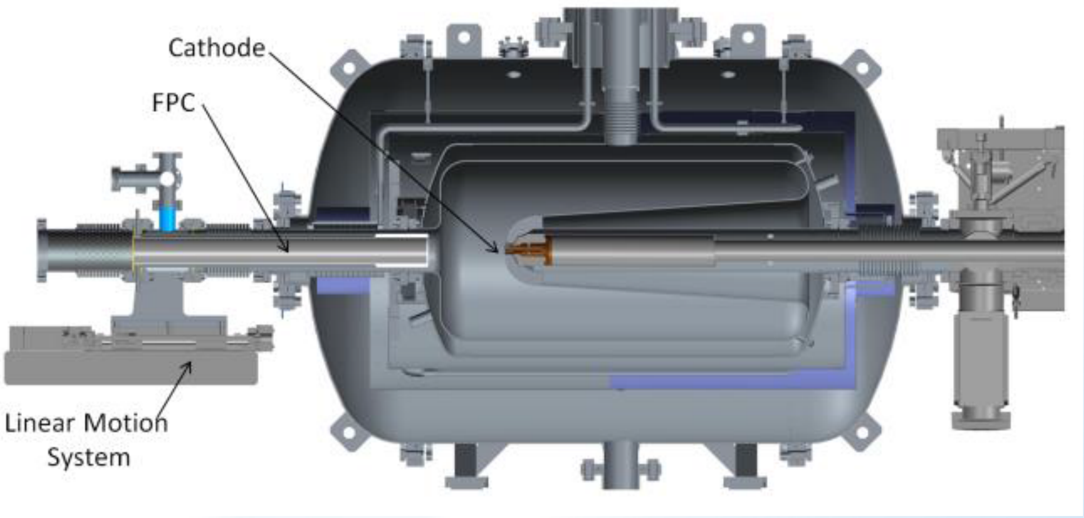
Quarter Wave Resonator SRF gun



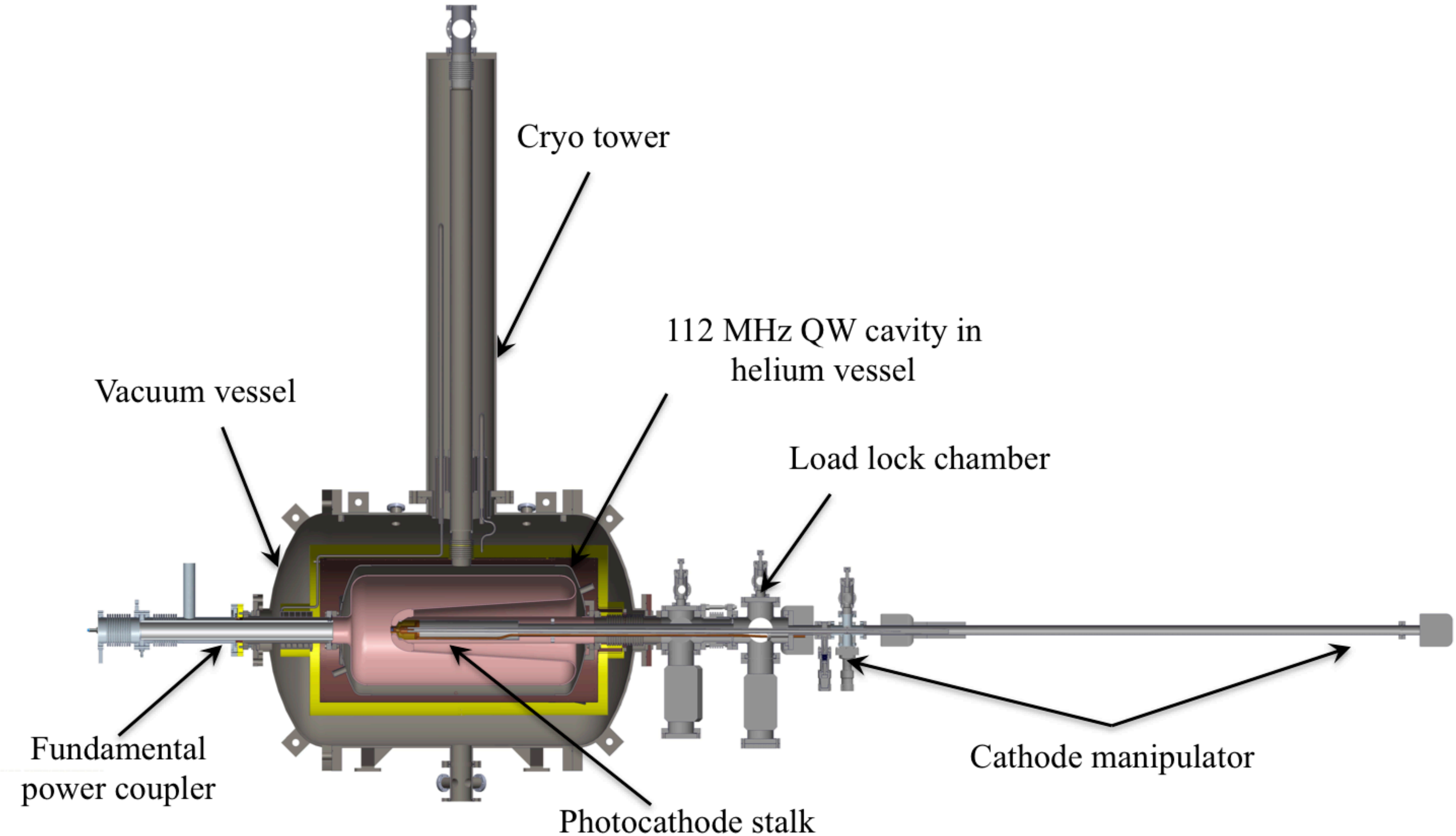
- A superconducting 112 MHz QWR was developed by collaborative efforts of BNL and Niowave. The cavity fabrication and first cold test in ahorizontal cryostat was part of an SBIR project at Niowave.
- Why 112 MHz?
  - ✧ Low frequency: long bunches – reduced space charge effect.
  - ✧ Short accelerating gap: accelerating field is almost constant.
  - ✧ Cathode does not have to be mechanically connected to SRF structure: flexibility in cathode types.
- The cryostat, tuner, fundamental power coupler, cathode stalk, etc. were developed as part of CeC PoP.
- A 2 kW solid state RF amplifier was purchased to feed the cavity. A digital LLRF system, based on RHIC LLRF platform, was built. The RF system is fully operational.

112 MHz SRF gun overview

- Electron beam will be generated by illuminating a CsK_2Sb photocathode with a green (532 nm) light from a laser.
- The photocathode is located in a high electric field. Immediate acceleration of the electrons to a high energy reduces emittance degradation caused by a strong non-linear space-charge force. The low RF frequency of the gun reduces effect of RF curvature on the beam.
- The gun will produce electron beam with up to 5 nC charge per bunch, 78 kHz repetition frequency. The bunch train repetition rate is equal to the revolution frequency of ion bunches in RHIC thus allowing us to cool ion one bunch.



SRF gun cryomodule

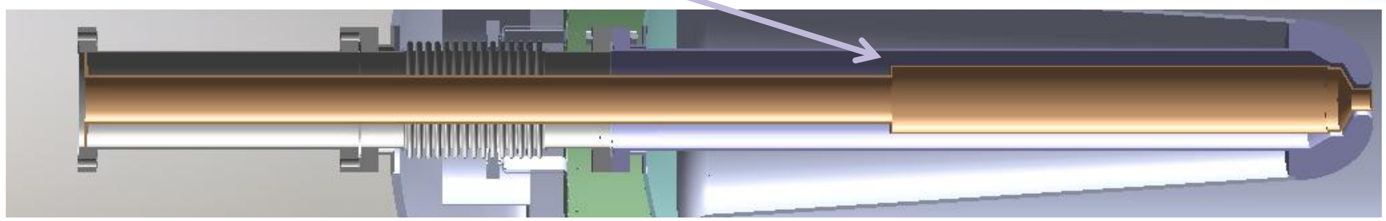


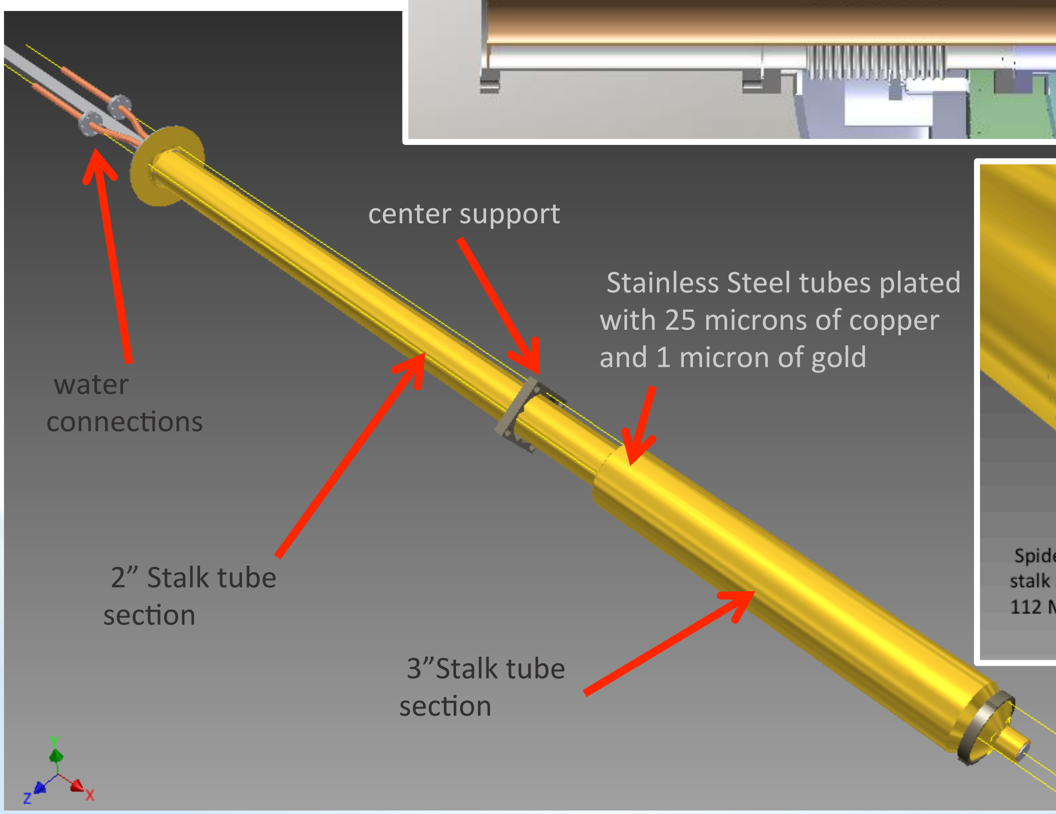
SRF gun parameters

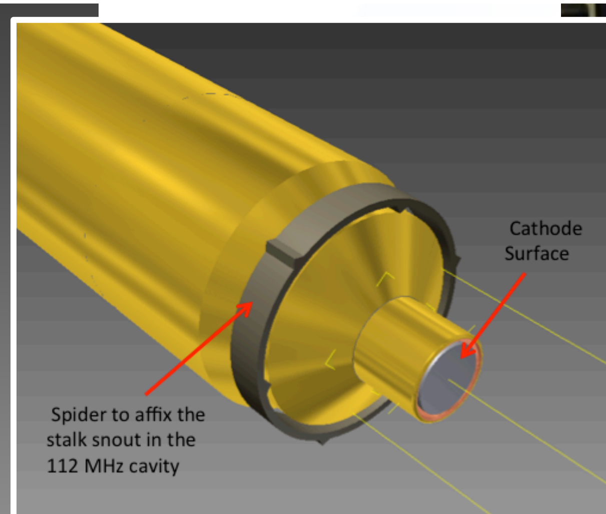
RF frequency	112 MHz
Maximum energy gain	2.0 MeV
Peak surface electric field	38.2 MV/m
Peak surface magnetic field	72.8 mT
Electric field at the cathode	14.5 MV/m
Bunch charge	1 to 5 nC
Bunch repetition frequency	78 kHz
R/Q	127.3 Ohm
Geometry factor	38.5 Ohm
Cavity Q_0 at 4.5 K	1.8e9
Cavity RF losses	17 W
RF losses in the cathode stalk	38 W
Frequency tuning range	78 kHz
Q_{ext}	1.25e7
Available RF power	2 kW
RF power amplifier	Solid State

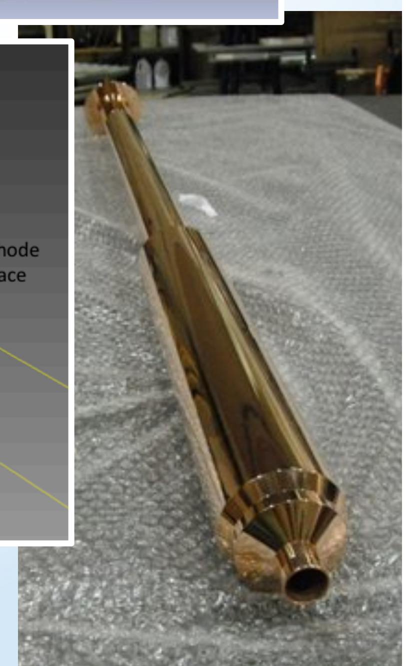
Cathode stalk design

- The cathode stalk is a hollow center conductor of the coaxial line formed by the stalk and the cavity.
- The stalk is shorted at one end and is approximately half wavelength long. It is permanently installed in the gun, but can be adjusted by ~5 mm longitudinally.
- A step at $\lambda/4$ from the short creates a quarter-wave impedance transformer and reduces RF losses in the stalk from ~65 W to ~25 W.
- The gold plating is aimed to reduce radiation heat load from the RT stalk to the cold (4.5 K) niobium.
- A small cathode puck is inserted inside the stalk and can be replaced when necessary with a new one.

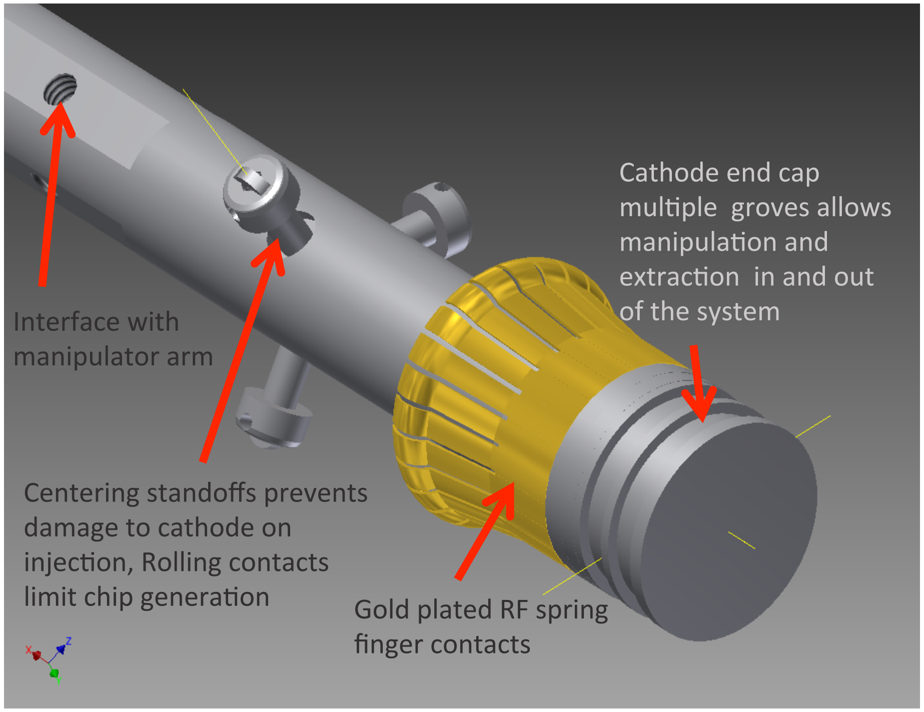


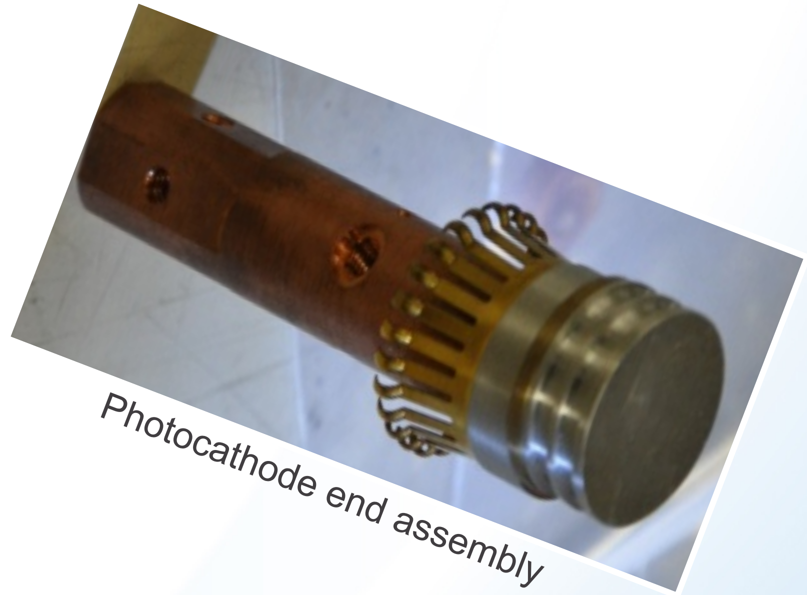






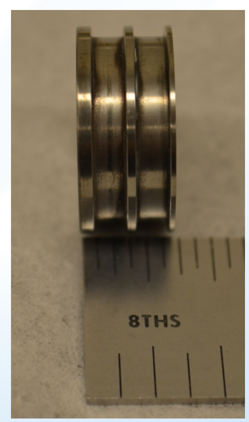
Photocathode end assembly



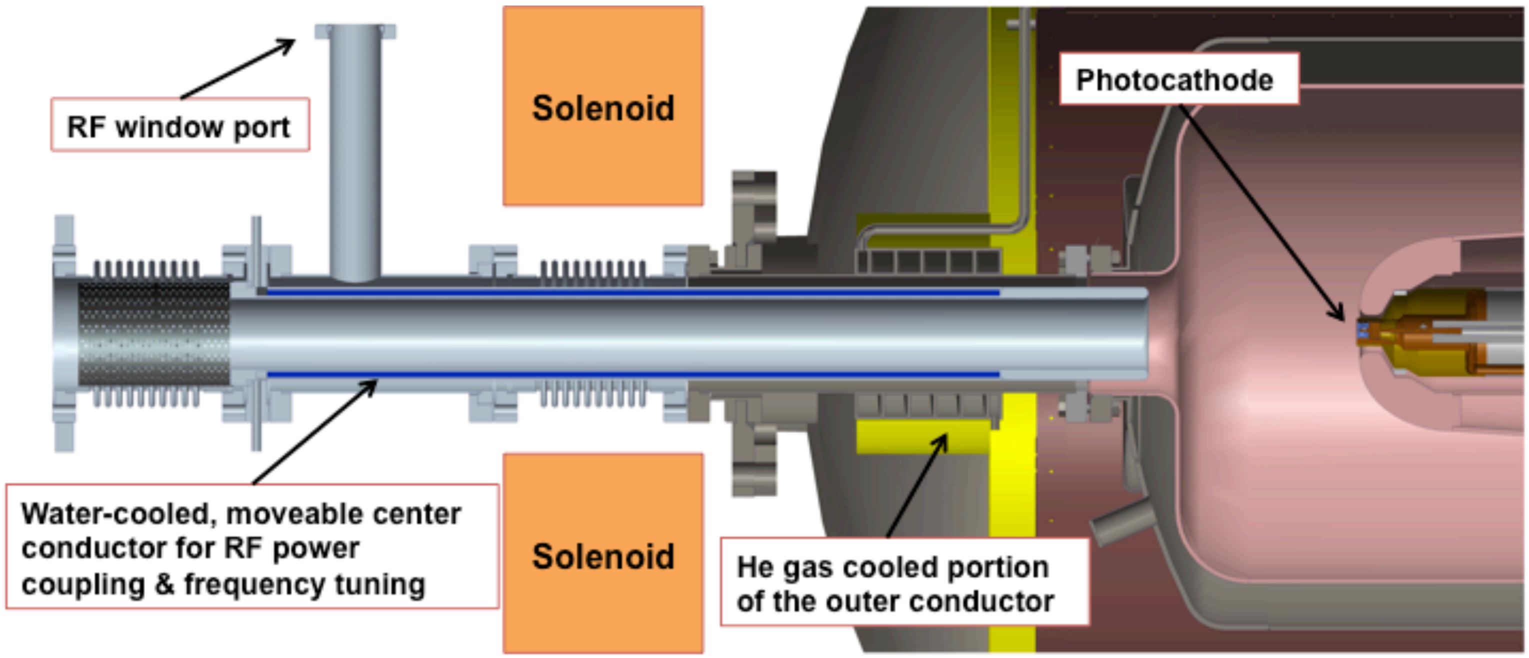


Photocathode end assembly

Cathode puck

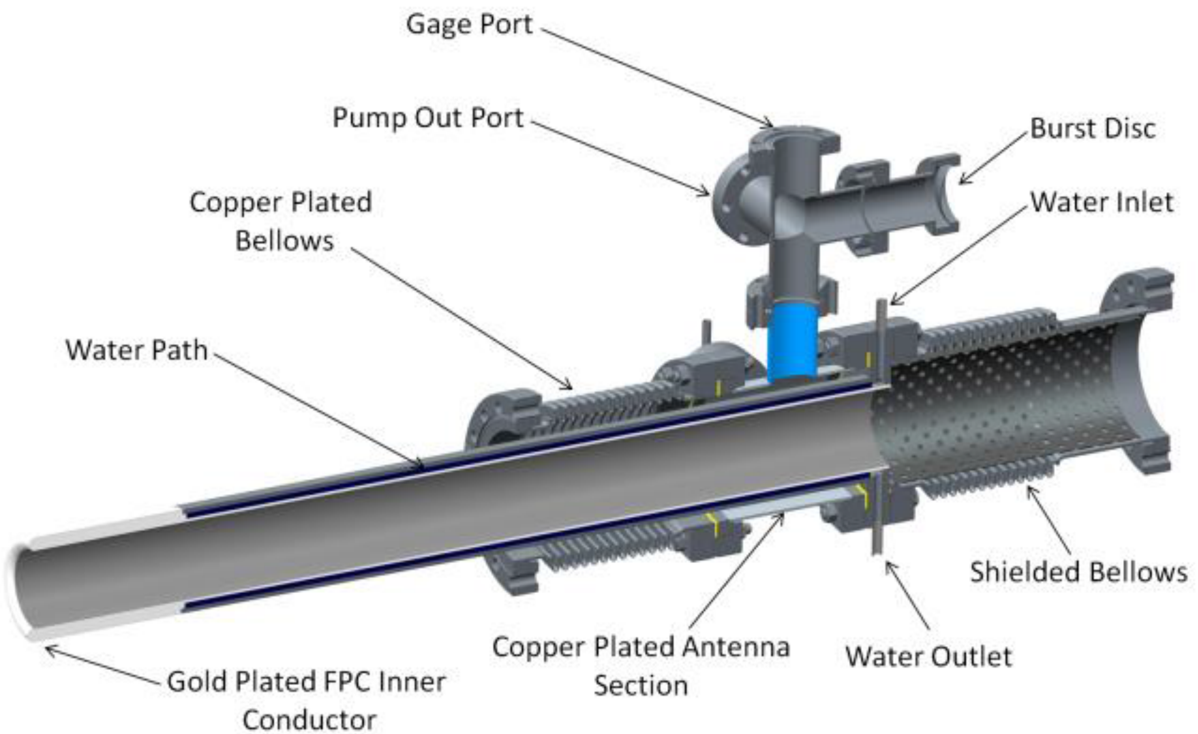


Fundamental Power Coupler / frequency tuner

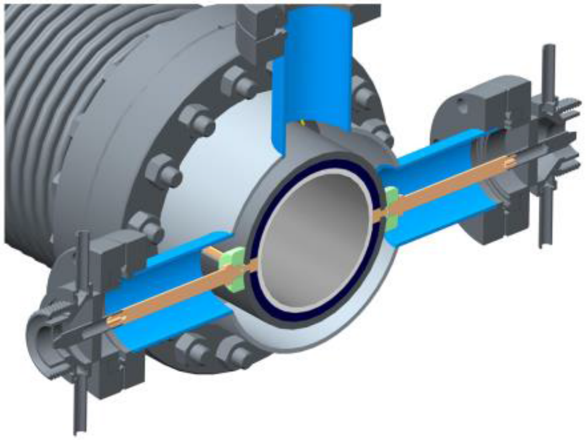


- Fundamental RF power coupling and fine frequency tuning is accomplished via a coaxial beam pipe at the beam exit port.
- With the travel of ±2 cm, the tuning range is ~6 kHz. Rough tuning is accomplished manually via mechanical linkages outside the cryomodule.
- The cooling of this assembly is quite challenging as in the extreme position (about 1 cm from the cavity gap) the dissipated power will exceed 1 kW.
- The center conductor and RF windows are water cooled. The outer conductor bellows (copper plated) are air cooled.
- The center conductor is gold plated to reduce heat radiated into cold SRF cavity.

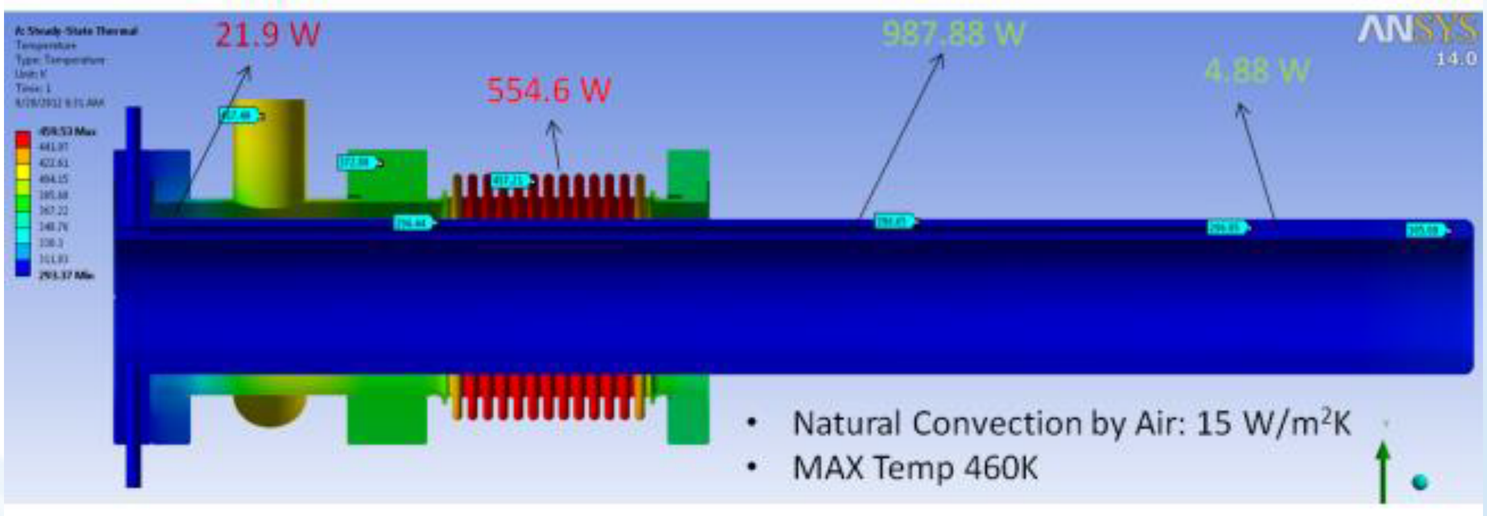
Fundamental Power Coupler



Fundamental Power Coupler (2)

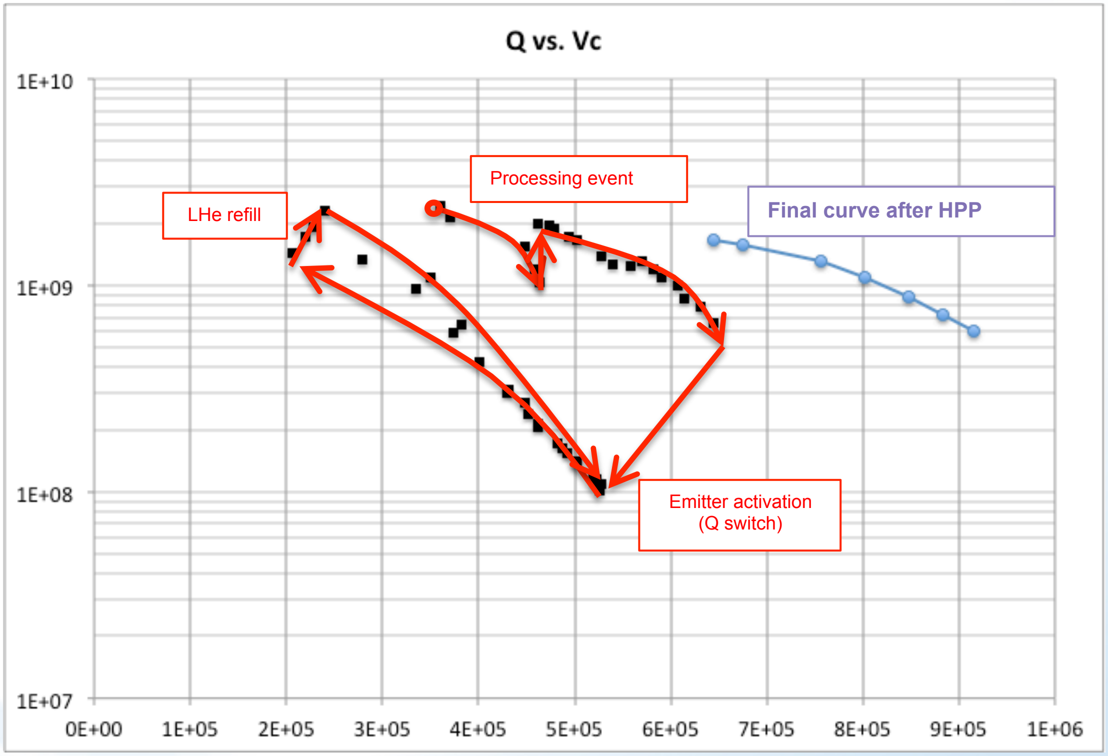


Vacuum feedthrough for connection of the coaxial cable to the FPC



Cold test at Niowave

- Prior to shipping to BNL, the SRF gun cryomodule was tested at Niowave in February of 2013 (w/o cathode and FPC/tuner assembly).
- We have encountered multipacting zones at very low fields, which were processed only after the RF input coupler (different from FPC/tuner assembly) was modified to increase its coupling to cavity.
- Eventually, after RF conditioning, the SRF gun cavity reached 0.92 MV, limited by insufficient radiation shielding at Niowave's facility.

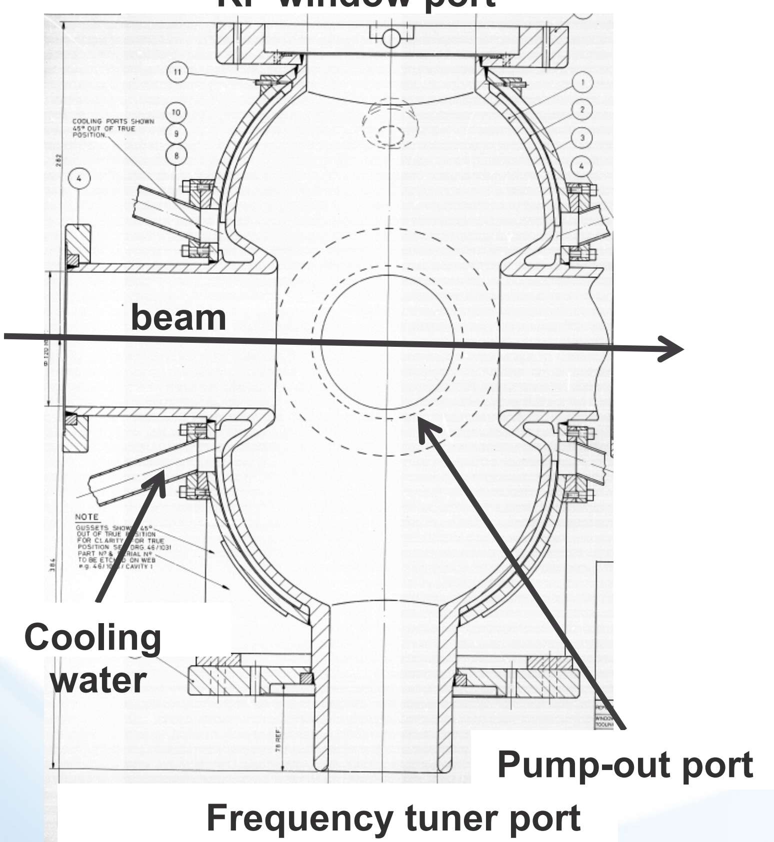


SRF gun conditioning

- The cryomodule was installed in RHIC tunnel (IR2) earlier this year. Installation of the cathode stalk and FPC/tuner assembly followed.
- Upon completion of all sub-systems, we began conditioning in November. Until RHIC cryogenic plant is up and running, we are filling the cryomodule from dewars and hence our conditioning run time is limited to 2 days per week at best. It will be much easier to continue conditioning as soon as RHIC is cold in January and we can take full advantage of its cryo system.
- At first, we have encountered multiple multipacting (MP) zones at low cavity voltages (below 200 kV), presumably in the FPC area. Conditioning is performed in pulsed mode with rep rates 1 Hz and 10 Hz, and with various pulse durations. Eventually managed to condition these zones and quickly go up to ~800 kV, where started to see multipacting in the cathode stalk.
- The latest conditioning run was last Friday, when we reached ~2 MV with 10-20 ms pulses, 1 Hz repetition rate. Limited by cryogenic trip: too much heat dissipation due to field emission (FE). Can operate stably at 1.25 MV.
- Some MP barriers are still active and have to be re-conditioned occasionally. Still a lot of FE at high voltages. More conditioning is required.
- The next round of conditioning will begin in January.

Normal conducting bunching cavities

- Two normal conducting 500 MHz single-cell bunching cavities are on loan from Daresbury Lab.
- The cavities were formerly used in SRS, operating at 300 kV.
- Fundamental power coupler is of a waveguide type coupled to the cavity via an aperture (port) at the cavity top, sealed with a disk ceramic window.

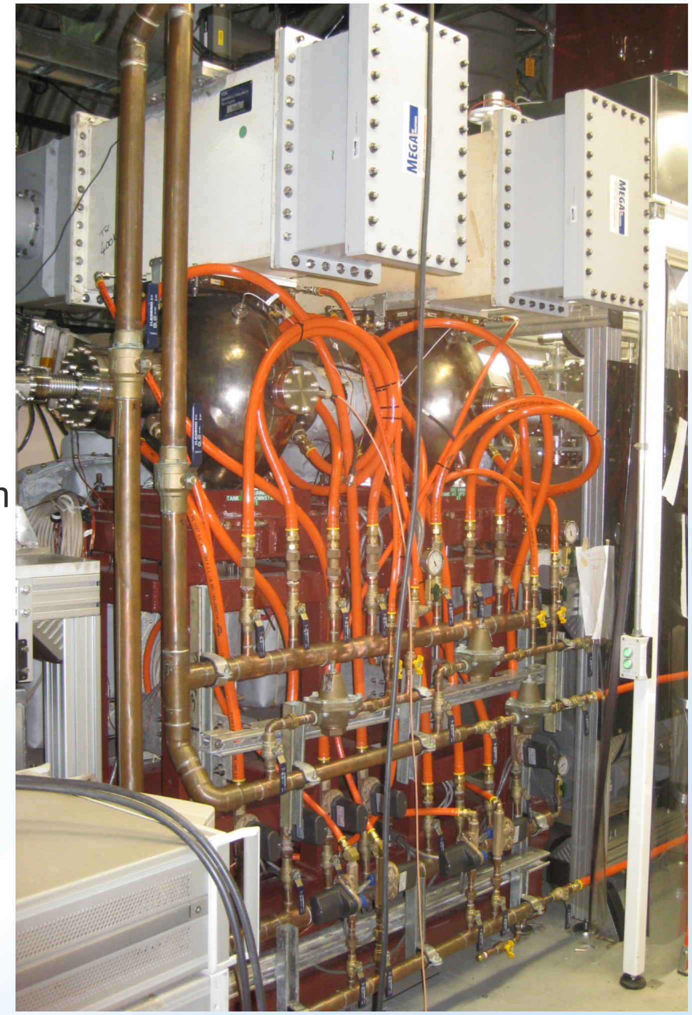


Parameter	500 MHz buncher
V_{acc}	300 kV
R/Q	178.5 Ohm
Geometry factor	38.2 Ohm
Q_0	31,000
Cavity wall RF power loss	16.3 kW
RF coupling	1
Available RF power for 2 cavities	50 kW

Status and test plans for bunchers

Cavities upon delivery

Refurbished cavities in the tunnel



- The cavities were delivered to BNL in early 2012.
- They undergone refurbishing, which included complete disassembly, particulate-free cleaning and re-assembly and vacuum bake.
- Then the cavities were installed in the RHIC tunnel and connected to a 50 kW IOT RF amplifier (DCX HPA by Comark), similar to the ERL HPA, and controlled with a digital LLRF based on the RHIC LLRF platform.
- Originally, the cavities were powered via a coaxial T, but that configuration strongly coupled them preventing proper operation.
- The T was removed and a 3dB hybrid RF power splitter was ordered to replace it.
- While we were waiting for the hybrid delivery, the cavities were conditioned to >300 kV one at a time.
- The hybrid was delivered and installed recently. A high power RF test of the final configuration will be performed soon.

Conditioning results of bunching cavities

Cavity #1:

- Optimum cavity resonant frequency was determined to be @ 499.933 MHz.
- 4 days of conditioning with multiple zones of multipacting observed.
- Able to reach 14.5 kW in CW mode with 310 kV sustaining for about 10 minutes, limited by the RF window temperature interlock at 33°C.

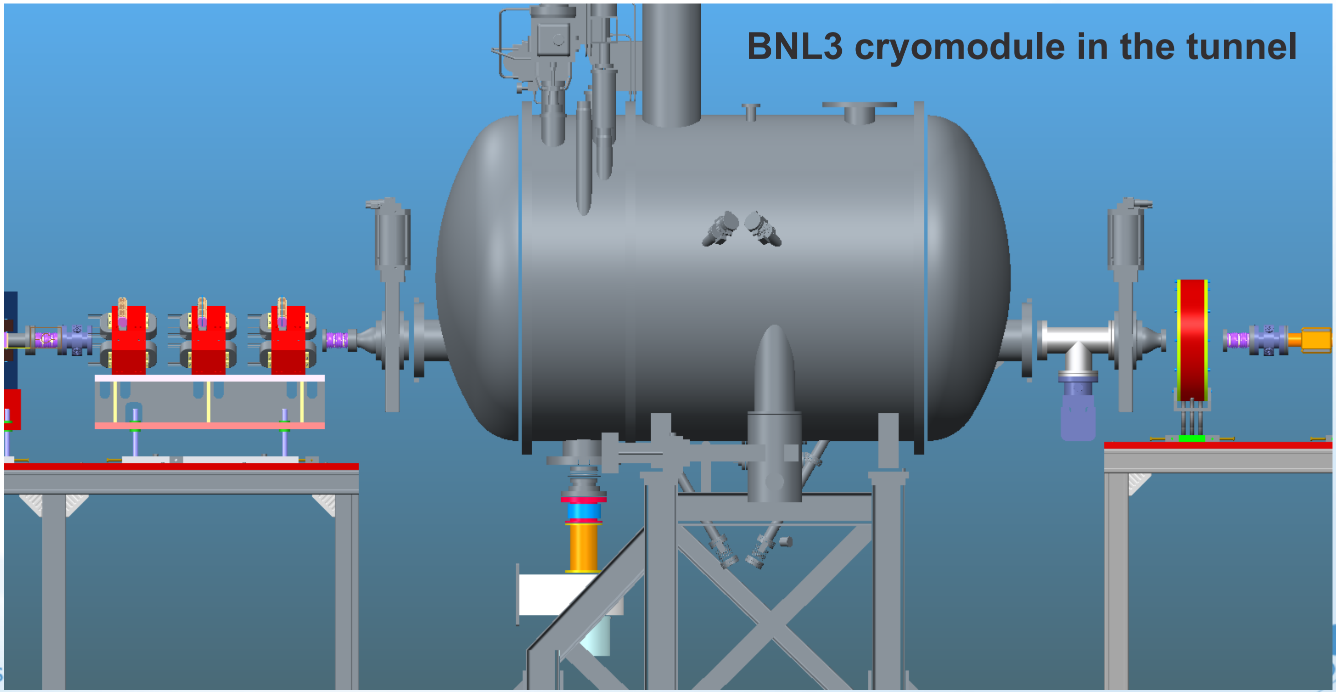
Cavity #2:

- By the time we begin conditioning this cavity, an automated conditioning was implemented.
- The conditioning application worked well and was intuitive to allow enough time for conditioning between each voltage step up.
- We were able to reach about 350 kV at 13.5 kW in CW regime after which a temperature probe caused MPS trips at 37°C.

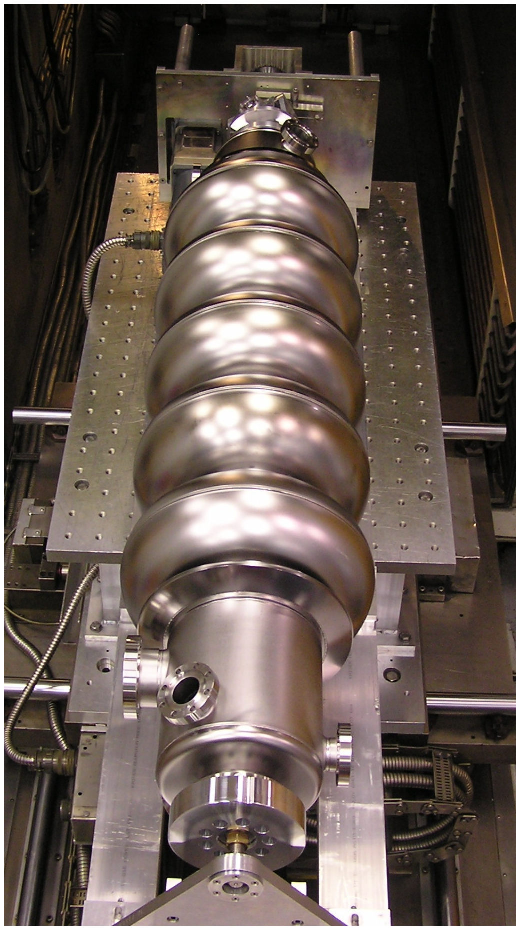
➢ Frequency tuner controls of both cavities were checked.

704 MHz 5-cell accelerating cavity

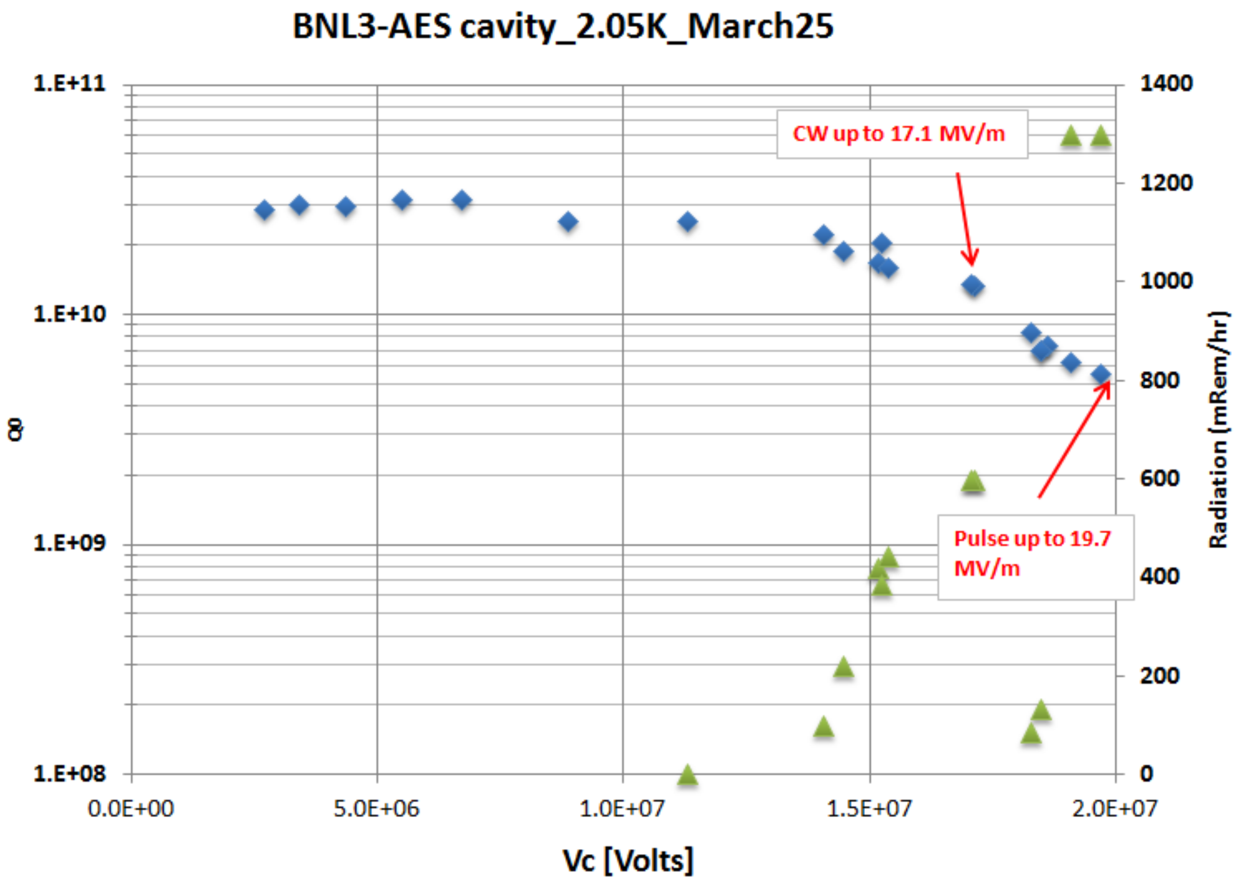
- The 5-cell SRF cavity (BNL3) will provide acceleration to increase the beam energy to 22 MeV. It was originally developed for high-current applications such as SPL and eRHIC.
- There are three ports at each large beam pipe of the cavity for HOM couplers, which will be blanked off in CeC PoP linac as there is no need for HOM damping.
- AES fabricated a full-scale copper model and the first niobium cavity (BNL3-1).
- Bulk BCP (120 um) of BNL3-1 was completed at AES, then the cavity was vacuum baked at 600°C for 10 hrs at BNL, which was followed by light BCP and HPR at AES.



Vertical test results



BNL3 cavity at AES

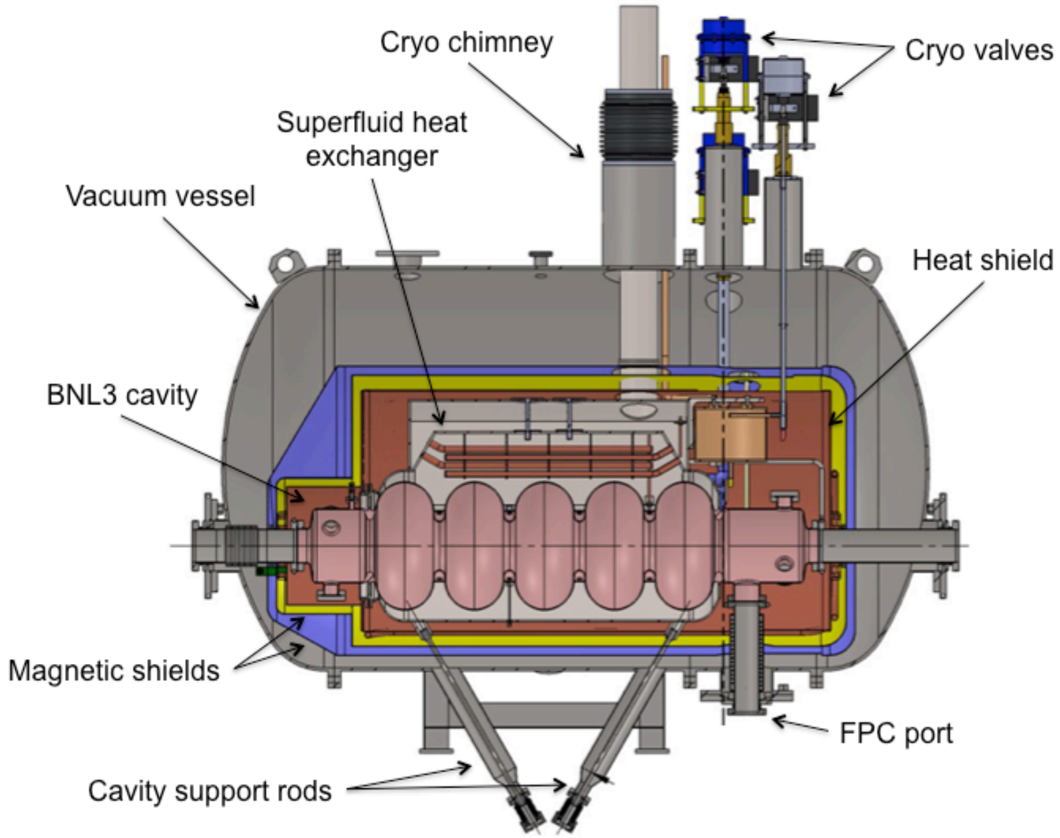


- The VTF testing was performed in March of 2013.
- The cavity reached 19.7 MV/m (due to an administrative limit on the facility at that time) with good Q_0 at lower fields. There was FE starting at about 15 MV/m.
- There was no time to re-clean the cavity and repeat the test, but the results were satisfactory to continue with CeC PoP cryomodule assembly.

Parameters of the BNL3 cavity

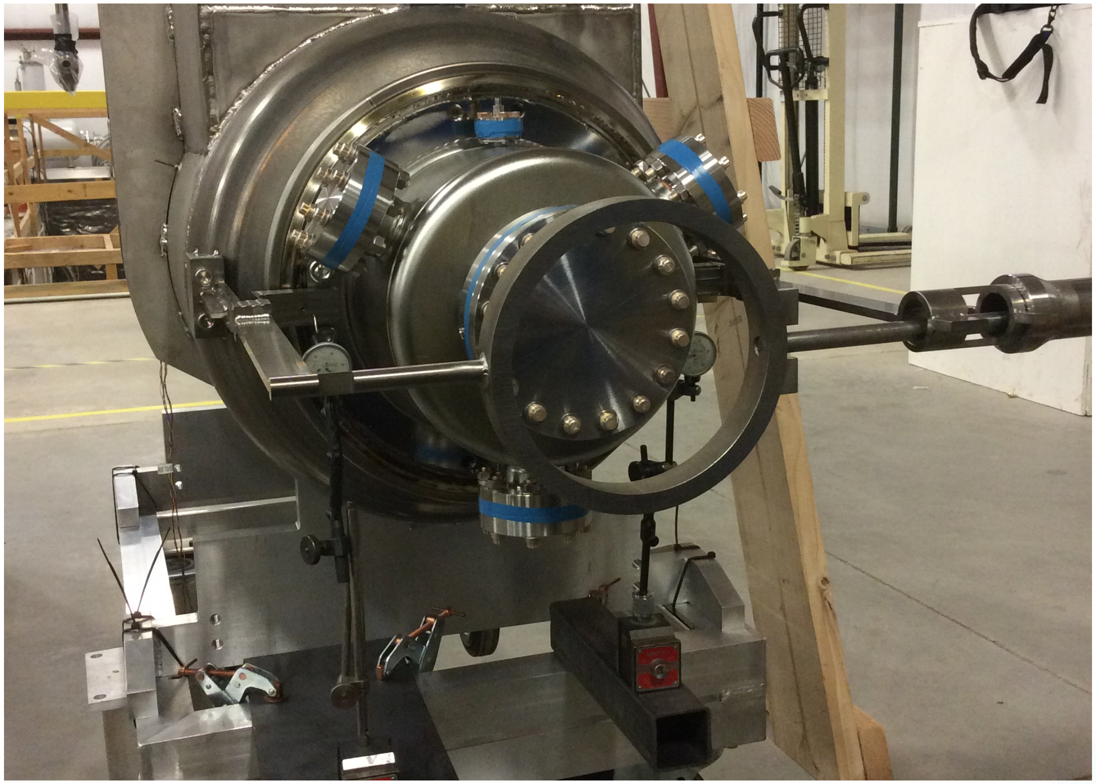
Parameter	704 MHz BNL3 cavity
V_{acc} [MV]	20
No. of cells	5
Geometry Factor	283
R/Q [Ohm]	506.3
E_{pk}/E_{acc}	2.46
B_{pk}/E_{acc} [mT/MV/m]	4.26
Q_0	$> 2 \times 10^{10}$
Length [cm]	158
Beam pipe radius [mm]	110
Max. beam power [kW]	7.8
Peak microphonics detuning [Hz]	12
Q_{ext}	2.8×10^{7}
Available RF power [kW]	20
Frequency tuning range [kHz]	> 78
Operating temperature [K]	1.9

CeC PoP 5-cell cavity cryomodule

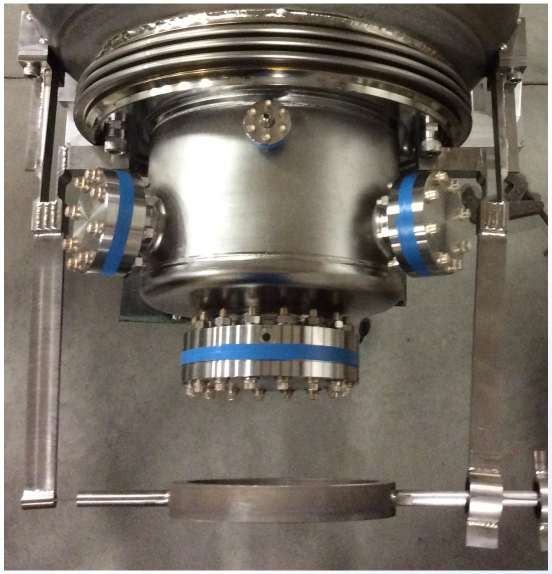


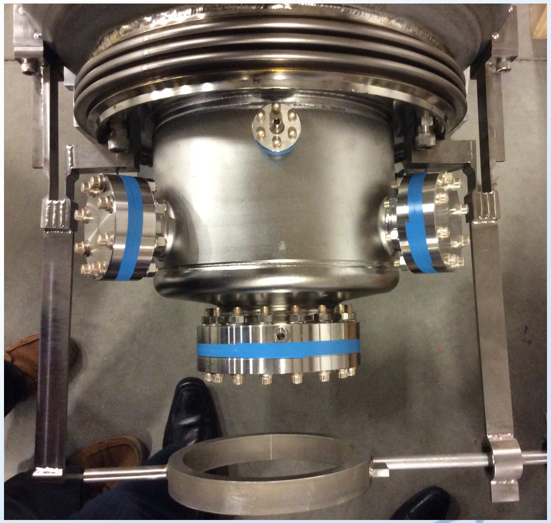
- The cryomodule was ordered from Niowave.
- In addition to standard components, such as thermal and magnetic shields, superinsulation, FPC, frequency tuner, the cryomodule will feature a SuperFluid Heat eXchanger (SFHX) to better isolate the cavity from mechanical noise induced by the 2 K pump skids and thus reduce detuning due to microphonics.
- FPC will be of a design similar to the one used on ERL 5-cell cavity. RF window/antenna ordered from Toshiba.

5-cell cavity frequency tuner



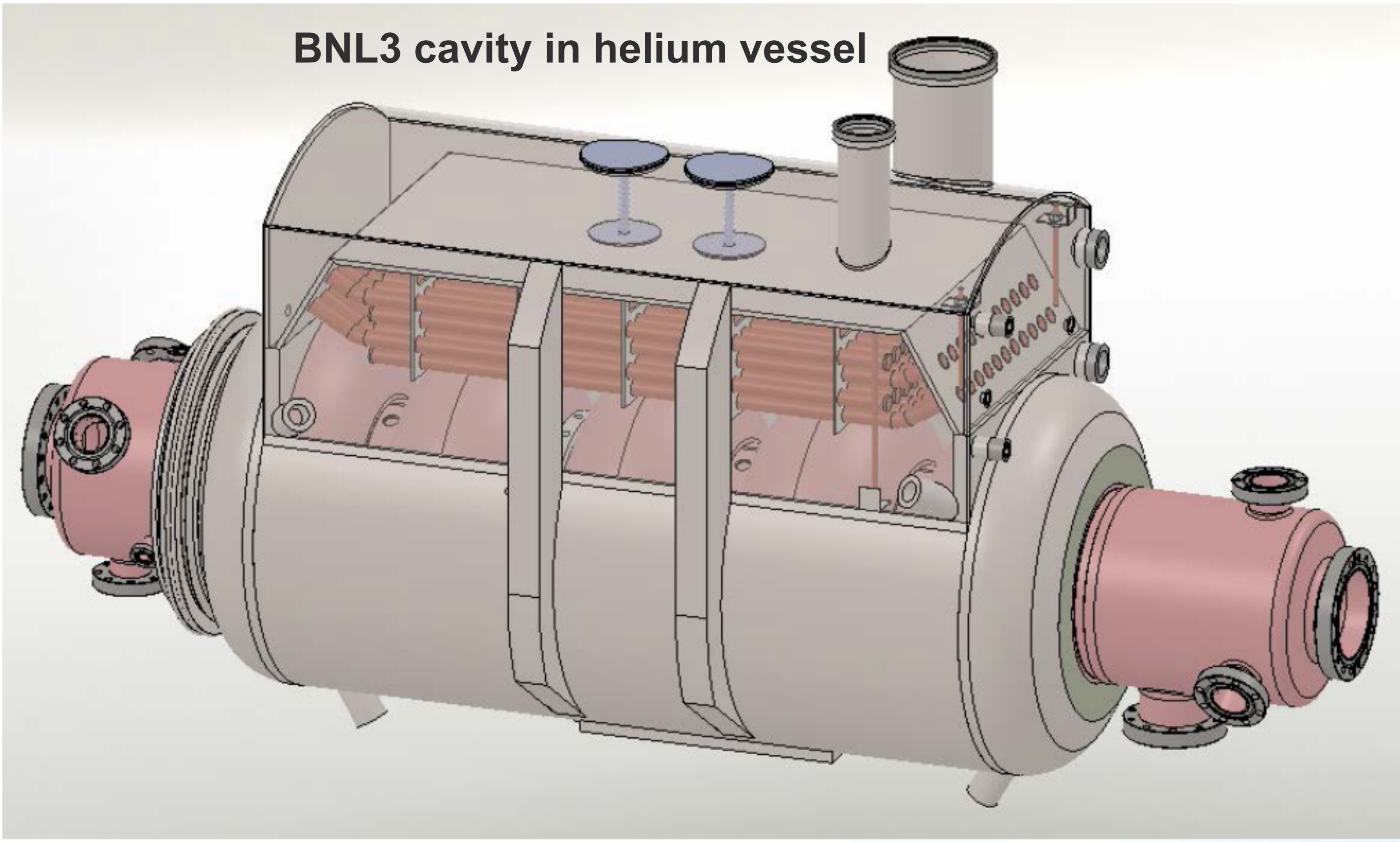
Extreme positions





- The tuner was designed after the frequency tuner designed for SRF cavities at HZDR. It should provide good de-coupling of the cavity from external microphonics and no backlash (flex joints are used).
- The tuner was assembled on the cavity in October and its operation was tested to BNL's satisfaction. The tuner design was approved.

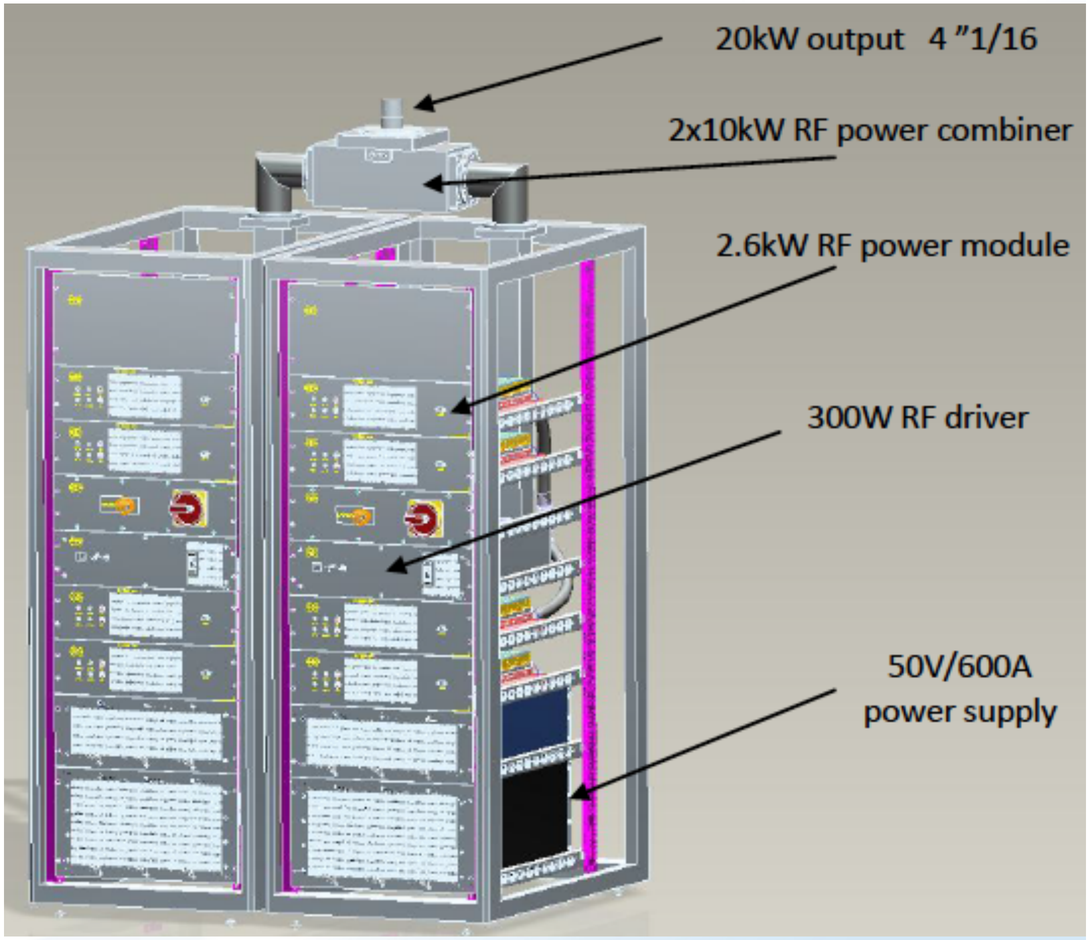
5-cell cryomodule status



- Critical design review (CDR) was held at Niowave in May. The cryomodule design was approved for fabrication, except the frequency tuner.
- The cavity helium vessel welding is complete and the cavity is at ANL for final BCP (10-30 um) / HPR, which is expected to be complete next week.
- Many of the other cryomodule components are complete, awaiting the cavity treatment.
- We expect the cryomodule to be delivered in spring of 2015.

20 kW RF power amplifier

- A 20 kW CW solid state RF amplifier was ordered from SigmaPhi.
- The amplifier fabrication is complete. The factory acceptance test is scheduled for next week.
- RF transmission line components will have to be ordered.



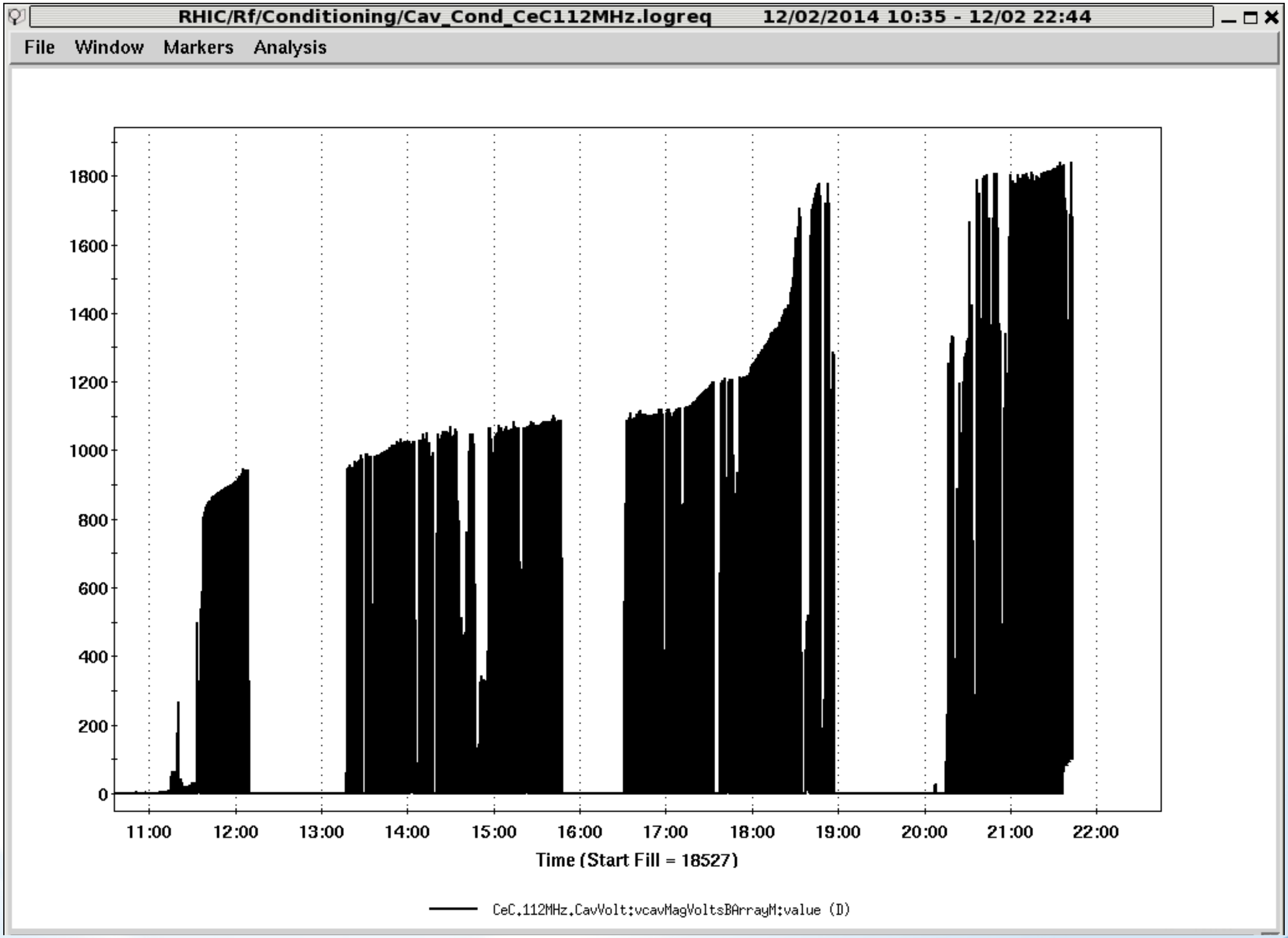
Summary

- Three SRF/RF systems are under construction for the CeC PoP experiment.
- The 112 MHz QWR SRF gun will provide a 2-MeV, high bunch charge electron beam. It is installed at IR2 and is under commissioning. So far the cavity reached ~2 MV in pulsed mode. FE and MP are limiting the voltage, further conditioning should improve the cavity performance.
- Two 500 MHz normal conducting bunching cavties are on loan from Daresbury as their contribution to the CeC PoP experiment. The cavities were refurbished and undergone particulate-free assembly. The system is installed in the RHIC tunnel. Both cavities were conditioned individually, exceeding the required voltage (300 kV). Commissioning the system with the two cavities operating in parallel will begin soon.
- The 704 MHz 5-cell accelerating SRF cavity will boost the beam energy to 22 MeV. A niobium cavity fabricated by AES was successfully tested in VTF and was shipped to Niowave for the cryomodule assembly. The cavity helium vessel with an integrated superfluid heat exchanger is welded to the cavity and the assembly is at ANL for the final cavity treatment. The cryomodule delivery to BNL is expected in spring of 2015.

Thank you!

Backup slides

SRF gun conditioning 12/02/2014



Signature of MP in the cathode stalk